LLNL-TR-739757

LAWRENCE LIVERMORE NATIONAL LABORATORY

Notes on LCW Activation Calculation for Neutron Imaging Operations in the North Cave of Building 194

S. G. Anderson

October 9, 2017

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Notes on LCW Activation Calculation for Neutron Imaging Operations in the North Cave of Building 194

Scott Anderson — May 2017

This note estimates the amount of activation that could be produced in the Facilities-provided Low Conductivity Water (LCW) that is proposed to be used for cooling of electromagnets and beam stops in the Neutron Imaging (NI) accelerator project in the North Cave of Building 194. The NI project collides a deuteron beam with various target materials to generate neutron beams for imaging applications. The deuteron beam is produced by an accelerator in the North Cave of B194, manipulated using water-cooled electromagnets, and terminated using water-cooled beam stops. Use of LCW is well-suited to this cooling application because the electromagnets and beam stops produce a moderate amount of heat (10s of kWs) but do not require tight tolerances on temperature. Use of closed-loop chillers for this application would be of significant cost to the program both in terms of hardware procurement and in terms of running the required electrical power to the North Cave.

The activity estimate relies on an MCNP analysis performed by H. Khater (Khater, 2017). The simulation uses ASE-limit values for the NI deuteron beam parameters (7.5 MeV and 400 micro-Amps) and dumps the beam into a TZM (Molybdenum alloy) beam stop with no shielding around the beam stop. This combination of beam stop material, lack of shielding, and beam intensity generates the maximum neutron flux rates expected by NI, and therefore gives a conservatively high estimate of activity induced in the cooling water. The simulations show a neutron dose rate that ranges from approximately 10 rem/hr near the North Cave ceiling to above 10^4 rem/hr at the TZM beam stop [see (Khater, 2017)].

The MCNP results were used in water activation calculations with the following assumptions: (1) the total volume of LCW in the North Cave is 250 liters, (2) the entire volume of LCW is exposed to the neutron flux averaged over the volume of the cave, (3) the LCW is irradiated for a period of 8 hours. The second of these assumptions is necessary to avoid a much more difficult simulation that tracks the detailed path of water through the various system components and is a reasonably conservative assumption, since most of the LCW volume is in the large diameter supply and return pipes mounted to the ceiling. The assumption that the water is irradiated for 8 hours allows us to evaluate the expected activation levels in the case of closed-loop chillers at the end of a run day. With these assumptions, the ALARA code was used to simulate the amount of activity induced in cooling water, given in Table 1:

Isotope	Activity at Shutdown (Ci)	Decay Constant (1/sec)
H-3	1.23E-09	1.78E-09
C-14	1.71E-12	3.85E-12
C-15	3.55E-08	2.83E-01
N-16	3.78E-05	9.72E-02

N-17	3.52E-08	1.66E-01
N-18	1.33E-07	1.12E+00
O-15	1.30E-07	5.67E-03
O-19	4.67E-08	2.58E-02

Table 1 Radionuclides and activity levels produced in 250 liters of water after 8 hours of NI operations.

In the case of LCW use, the water is not exposed to neutron radiation for 8 hours, but enters the radiation area, flows through the magnets and beam stops, and exits in a much shorter time. The activity levels given in Table 1 can be used however, to calculated the radionuclide production rates. The time derivative of the number of atoms of a specific radionuclide is given by:

$$\frac{dN}{dt} = -\lambda N + \phi, \quad \textit{Equation 1}$$

where λ is the characteristic decay constant, and ϕ is the production rate. If the production rate is a constant in time, the solution is given by:

$$N(t) = \frac{\phi}{\lambda}\left(1 - e^{-\lambda t}\right). \quad \textit{Equation 2}$$

The production rates of the radionuclides listed in Table 1 can therefore be calculated using the listed activities and solving for ϕ with $t = 8$ hours:

$$\phi = \lambda N(8\text{ hrs})/\left(1 - e^{-\lambda \cdot 8\text{ hrs}}\right). \quad \textit{Equation 3}$$

Isotope	Production Rate (atoms/sec)
H-3	8.90E+05
C-14	5.70E+05
C-15	1.31E+03
N-16	1.40E+06
N-17	1.30E+03
N-18	4.93E+03
O-15	4.81E+03
O-19	1.73E+03

Table 2 Radionuclide production rates in 250 liters of water for NI operation.

The time dependence of the activity concentration is found by multiplying Equation 2 by λ, and dividing by the volume of LCW in the North Cave, V:

$$a(t) = \frac{\phi}{V}\left(1 - e^{-\lambda t}\right). \quad \textit{Equation 4}$$

For isotopes with half-lives shorter than the transit time, T, of LCW through the radiation area the activity concentration will approach the saturation limit, $a_{sat} = {}^{\phi}/_{V}$. For the long-lived isotopes, H-3 and C-14, the activity concentration leaving the North Cave will be $a \approx \frac{\phi\lambda T}{V}$. An estimate of the flow rate of LCW in the North Cave can be made based on the pressure differential between the supply and return lines and the geometry of the various cooling lines. A conservatively low estimate for this rate is 10 liters/second, given this and the assumed total volume of 250 liters, the LCW transit time would be 25 seconds. As an additional conservative buffer, the transit time is taken to be 30 seconds in the calculations shown below.

The activity concentrations of radionuclides in LCW leaving the North Cave during NI operation are given in Table 3.

Isotope	Activity Concentration in N Cave LCW return (pCi/ml)	Activity Concentration in B194 LCW return (pCi/ml)	NRC Limit Effluent Concentration in Water (pCi/ml)
H-3	5.14E-06	1.29E-06	1000
C-14	7.12E-09	1.78E-09	30
C-15	1.42E-01	1.50E-09	—
N-16	1.43E+02	1.05E-01	—
N-17	1.40E-01	1.63E-06	—
N-18	5.33E-01	9.84E-31	—
O-15	8.13E-02	1.45E-02	—
O-19	1.01E-01	5.35E-03	—

Table 3 Activity concentration of radionuclides in LCW leaving the North Cave and leaving B194 resulting from NI operations. The NRC Effluent Concentration limits are shown for comparison.

Table 3 also gives the activity concentrations of LCW in the B194 return lines assuming an addition 60 second transit time required for the water to be transported out of the building and assuming a factor of four dilution from mixing with LCW return from the South Cave, Accelerator Cave, and Modulator Building. For comparison, the table also gives the limiting values set by the Nuclear Regulatory Commission for effluent concentrations in water. These limits are the activity concentration values that would be required to receive a dose of 50 mrem from “continuous ingestion” of the water for one year. For isotopes with half-lives less than 2 hours and decay mode other than alpha emission or spontaneous fission, NRC does not list an effluent concentration limit in water. For H-3 and C-14 we find that the expected concentrations leaving B194 are 9-10 orders of magnitude below the NRC limits and therefore do not pose a hazard from ingestion.

Except for the long-lived isotopes, H-3 and C-14, the remainder of the isotopes listed in the tables above have sufficiently short half-lives and low concentrations for the ingestion hazard to be considered negligible. H-3 and C-14 activity concentration will increase over time however, and this buildup should be evaluated. Using the production rates in Table 2 and assuming 2000 hours of operation in a year, the total activity generated is calculated and given in Table 4. The activity will be dispersed uniformly in the entire volume of LCW and so the concentrations can be calculated using the total volume of LCW, 583,000 gallons (Ocampo, 2017).

Isotope	Activity Buildup in LCW after one year (Ci)	Activity Concentration in LCW after one year (pCi/ml)	NRC Limit Effluent Concentration in Water (pCi/ml)
H-3	3.09E-07	1.29E-06	1000
C-14	4.27E-10	1.78E-09	30

Table 4 Buildup of total activity and activity concentration after one year of NI operation compared to NRC effluent limits.

As the table shows, after one year of buildup the activity concentrations of H-3 and C-14 in LCW remain 9-10 orders of magnitude below the NRC limits. Given the fact that there is a finite cycle time for water in the LCW system (due to leaks, purges, etc.) it is improbable that the activity concentrations of H-3 and C-14 would ever rise significantly higher than those listed in Table 4. The ingestion hazard should therefore be considered negligible. In the extreme case that the H-3 activity listed in Table 4 were somehow concentrated and entirely ingested, then using the Committed Effective Dose Equivalent (CEDE) value of 64 rem/Ci, the dose received would be only 20 microrems. Similarly, the dose from ingesting the entire amount of C-14 would be about 1 microrem.

Works Cited

Khater, H. (2017). *Radiation Safety Analysis for the NI System in B194.*
Ocampo, R. P. (2017). private communication.